Radar and Rain Gauge Rainfall Discrepancies Driven by Changes in Atmospheric Conditions

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Key Points:

- Meteorological elements influence radar-gauge rainfall discrepancy
- Radar overestimate rainfall in low humidity condition and vice versa
- The cold season has more explicit humidity induced rainfall variation trend than the warm season in the UK

Abstract

This study explores humidity impacts on radar-gauge rainfall discrepancies in three-dimensional spatial fields. The results indicate that the radar overestimates rainfall when relative humidity is low, whereas the increment of rainfall is detected by the gauge when relative humidity maintains high. The proposed linear models exhibit desirable fitting correlations between the mean relative humidity and the average rainfall deficits especially in the cold season with a higher correlation coefficient *r* (0.837). The results of model generalizations show a considerable improvement in the radar-gauge rainfall agreement as RMSE declines evidently from 4.002 mm/h to 1.057 mm/h for rainfall events in the cold season and from 4.615mm/h to 1.048 mm/h in the warm season. This is the first study as a proof of concept in quantifying relative humidity impacts on radar-gauge rainfall discrepancies in three-dimensional fields, which is worthwhile considered as an essential component in radar data correction for hydro-meteorological applications.

Keywords: Radar-Gauge Rainfall Discrepancies, Relative Humidity, WRF, Radar Rainfall Correction

1 Introduction

Weather radars enable instantaneous precipitation estimation with areal coverage at both high temporal and spatial resolutions, thus, they are widely adopted in the hydrological and meteorological applications. However, due to the complex measurement process and fluctuated environmental conditions, radar rainfall estimates are prone to large uncertainties such as ground clutter, beam blockage, anomalous propagation, vertical reflectivity variation, bright band etc. [*Wilson and Brandes*, 1979; *Borga et al.*, 2002; *Villarini and Krajewski*, 2010; *Hazenberg et al.*, 2013; *Kirstetter et al.*, 2013]. The conventional radar estimates are comprehensively assessed with rain gauge measurements to effectively correct their systematic biases. The common practice for radar-gauge adjustment incorporates the estimation of a mean field bias correction based on gauge-radar ratios [*Brandes*, 1975; *Collier*, 1986; *Smith and Krajewski*, 1991; *Seo and Breidenbach*, 2002] or through the use of geostatistical techniques by applying direct weighted interpolation algorithms to merge radar and gauge measurements [*Krajewski*, 1987; *Creutin et al.*, 1988; *Velasco-Forero et al.*, 2009; *Berndt et al.*, 2014]. Albeit deterministic or statistical methods provide quantitatively practical information in radar rainfall adjustment for operational real-time use in hydrological applications [*Garcia-Pintado et al.*, 2009; *Sideris et al.*, 2014], only a few studies deal with the synoptic regimes' impacts on physical processes of precipitation variation.

Previous studies have analysed the inconsistency of radar and gauge measurements influenced by meteorological variables such as temperature and humidity. *Stewart et al.* [1984]; *Kitchen* [1997]; and *Cluckie et al.* [2000] explored the effects of the variation of the vertical profile of reflectivity (VPR) with melting layer as an error source of radar measurements. *Rosenfeld and Mintz*, [1988] and *Li and Srivastava*, [2001] identified that raindrops could be considerably evaporated especially for light-moderate rain in semiarid regions. *Austin* [1987] found that the radar and surface rainfall were highly relevant to meteorological factors, in which radar could underestimate surface rainfall when raindrops significantly accreted under fog formation conditions, whereas radar overestimated surface rainfall when the droplets were prone to evaporate falling through arid environments. However, only integrating discrete liquid water content and relative humidity to assess the meteorological impacts on precipitation variation is limited to interpret the radar and gauge discrepancies. Therefore, an extensive understanding of synoptic regimes on rainfall changes is desirable to be investigated. This study presents a preliminary study on quantifying the impacts of humidity on radar rainfall measurements.

In this context, this study proposes a new scheme to quantify humidity effects on the precipitation changes from radar to surface. The proposed scheme is to formulate a more practical radar-gauge relationship through the joint use of atmospheric factors. This is a novel attempt to embed the predominant meteorological elements in radar-gauge rainfall estimation, which could be an essential component in fundamental processes for radar bias correction in the future.

2 Methods

2.1 Study Area and Datasets

The study area is in the north of England, UK, which is covered by 3 radars and a dense rain gauge network in Figure 1. This study area is mostly covered with high ground especially in the northern part and orographic enhancement of precipitation can contribute to aforementioned radar errors. The radar data collected from a network of 15C-band rainfall radars is processed by RADARNET IV system through quality control by integrated correction algorithms (e.g. clutter and beam blockage identification, correction of VPR, bright band removal etc.). The pre-processed radar data is then composited into a single rainfall product with spatial/temporal resolutions of 1km/5min [*Harrison et al.*, 2000, 2009]. 207 Tipping-Bucket Rain gauges (TBRs) with 15-min temporal resolutions were located in the study area (see Figure 1). Since TBR measurements are prone to errors such as blockage, atmospheric effects as well as sampling errors, thus, it is crucial to minimize errors in gauge measurements if used as the ground truth. Therefore, the rain gauge data was quality-controlled by removing those gauges with significant deviation with the nearest neighbors in this analysis [*Rico-Ramirez et al.*, 2015]. Both rainfall measurements are accumulated to generate time series with a temporal resolution of 1 hour and covering a period from 2007 to 2010, only year 2008 is selected as it contains relatively complete data after a quality check.

The meteorological dataset is collected from the ERA-40 global reanalysis data produced by the European Centre for Medium-range Weather Forecasts (ECMWF). 6 typical rainfall events are selected to test the scheme of this study listed in Table 1.

2.2 Model

The Weather Research and Forecasting (WRF) atmospheric model is selected in this study because of its wide application and tremendous advantages over other numerical weather models [*Skamarock et al.*, 2008; *Dai and Han*, 2014]. The WRF model mainly contains pre, modelling and post-processing systems to obtain the desired meteorological products. The three-dimensional temperature profiles derived from WRF can be used to provide the premise of analyzing the relationship between atmospheric elements and rainfall discrepancies below the freezing level. Based on the vertical temperature profiles from the WRF vertical layers, it has been found that the freezing levels in two rainfall events in the cold and warm seasons are about 1.1 km and 2.0 km respectively above the ground, i.e. 8^{th} and 10^{th} WRF layer. The relative humidity is derived by National Center for Atmospheric Research Command Language libraries based on the temperature, pressure and water vapor WRF outputs in the post-processing system [*Skamarock et al.*, 2008; *Wang et al.*, 2016]. Only the lowest 7 WRF layers are extracted not only because the relative humidity is clearly stratified within these ranges beyond which most values remains in saturated conditions, but also to avoid the bright band effects as the freezing level is above the 7^{th} WRF layer.

3 Results

Temperature and humidity vary vastly in wet and dry seasons in this study area [*Martyn*, 1992] and all 6 rainfall events categorized into cold (Event 2, 3, 4) and warm (Event

1, 5, 6) seasons are analysed respectively to highlight the environmental effects. The rainfall rate deficit (P_{G-R}) which represents the measurements of gauge minus radar is used to describe its variation effected by the synoptic regimes. However, it is unrealistic to consider the whole plain area to illustrate the meteorological impacts in three-dimensional coordinates. Alternatively, all gauges along with their corresponding radar pixels are exclusively selected to specifically analyze how the relative humidity interacts with the rainfall rate deficits. Since the purpose of this research is to correct radar rainfall based on gauge measurements especially for large P_{G-R}, thus, those absolute rainfall deficits ($|P_{G-R}|$) less than 2 mm/h are excluded to avoid the uncertainties brought by either gauge or radar itself rather than affected by the meteorological process.

Figure 2 describes the relationship between mean RH values ($\overline{\mathrm{RH}}$ denoted as $\frac{\sum_{i=1}^{h} RH_i}{h}$ where h is the total number of WRF layers) and P_{G-R} (shown as the blue bar in zoomed-in subfigure of Figure 2a) in cold and warm events. The average value of P_{G-R} ($\overline{P_{G-R}}$) (shown as the red bar in zoom-in subfigure of Figure 2a) in each $\overline{\mathrm{RH}}$ interval, e.g. 75%≤ $\overline{\mathrm{RH}}$ ≤80%, $\overline{P_{G-R}}$ = -2.4 mm/h, aims to explicitly describe its entire trend with $\overline{\mathrm{RH}}$ variations. As depicted in Figure 2a-2c, P_{G-R} is mainly distributed in high $\overline{\mathrm{RH}}$ intervals, moreover, an intuitive summary can be drawn that $\overline{P_{G-R}}$ has a consistent change with $\overline{\mathrm{RH}}$ as $\overline{P_{G-R}}$ is rising with $\overline{\mathrm{RH}}$ increase and $\overline{P_{G-R}}$ transits from negative to positive when $\overline{\mathrm{RH}}$ is higher than 90%. Compared with the cold situation, P_{G-R} is evenly scattered in particular for Event 5 in Figure 2f where most values of P_{G-R} are located at $\overline{\mathrm{RH}}$ ranging from 60% to 80% in warm situation. $\overline{P_{G-R}}$, in general, rises with the increase of $\overline{\mathrm{RH}}$ in Event 5 and Event 6 in Figure 2f and Figure 2g respectively, though $\overline{P_{G-R}}$ is negative even in saturated humidity conditions except when 70≤$\overline{\mathrm{RH}}$≤75 in Event 1 in Figure 2e.

The clear tendency between $\overline{\mathrm{RH}}$ and $\overline{P_{G-R}}$ shown in cold and warm rainfall events are all extracted and theoretically extended by fitting them into a standard linear regression model for better comparison in Figure 2d and Figure 2h. The correlation coefficient (r, dimensionless) is used to assess the goodness of fit. The fitted model equations as well as the model performance indicators are also depicted in both figures. In general, a clear visual agreement between $\overline{\mathrm{RH}}$ and $\overline{P_{G-R}}$ can be identified in rainfall events of both seasons. The linear model in cold events fits considerably well as r reaches 0.837. The linear regression model for the warm events in Figure 2h exhibits poorer fitting results with lower r (0.514) compared with the cold events. Moreover, it is observed that underestimation/overestimation of the gauge rainfall from the radar is magnified in the cold situation as the linear line is more tilted than the warm situation. An unambiguous transfer of $\overline{P_{G-R}}$ when $\overline{\mathrm{RH}}$ beyond 90% in both situations additionally emphasizes its strong correlation with $\overline{\mathrm{RH}}$. The regression effects could possibly be improved if incorporated with more data. Nevertheless, the current results are capable of acting as a proof of concept in building an applicable rainfall-humidity relationship for practical applications. As a consequence, the results derived from all rainfall events in both seasons further quantitatively strengthen the premise from *Austin* [1987] in which of the low RH can result in radar rainfall overestimation, whereas rainfall is underestimated by radar when RH maintains in high magnitudes based on the analysis between relative humidity and radar-gauge rainfall deficits. The proposed linear regression models are then applied in both the cold and warm rainfall events separately and Root Mean Square Error (RMSE, Unit: mm/h) is used to evaluate the model performances on the radar rainfall rate corrections. Table 2 shows the comparisons before and after integrating the proposed linear models on rainfall events in the cold and warm seasons. It can be concluded that radar rainfall rate is improved evidently as RMSE dropped considerably after model corrections in both situations. For the cold situation, the overall RMSE of the raw radar-gauge rainfall agreement is 4.002 mm/h, being reduced to 1.057 mm/h with model correction. Note that especially for Event 2, which has the largest RMSE (4.740 mm/h) with uncorrected data, declines dramatically to 0.842 mm/h after correction. Compared with the cold situation, the overall RMSE for the warm seasons is 0.613 mm/h higher, both Event 1 and Event 5 have large RMSEs which are above 4.000 mm/h though Event 6 has the lowest RMSE (2.868 mm/h) for the uncorrected radar-gauge rainfall rates. The results are improved substantially after applying the proposed model as the RMSEs have decreased by 3.567 mm/h and 4.306 mm/h for overall events and Event 1 respectively.

4 Discussion

In this study, the rainfall rate variation from radar to surface is systematically explored with relative humidity. A quantification method is proposed to elaborate the relationship between average rainfall rate deficits and mean relative humidity in both the cold and warm seasons. The results of model generalizations show the proposed method has a good performance in improving the agreement between radar and gauge rainfall. However, some key concerns still need to be highlighted. Firstly, the radar data is processed and composited with 3 radars after quality control and correction, thus, the elevation of radar data used in the radar mosaic cannot be distinguished within stratified levels, which leads to the difficulty to extract the precise WRF layers to accurately model rainfall variation with WRF products. Moreover, it is acknowledged that large uncertainties are still associated with radar rainfall estimation, e.g. signal attenuation can't be accurately corrected especially for single polarization radar and short wavelength radar (C-band and X-band), due to the errors of measurements, uncertainties of parameter, the observational system limitations and the complex physical processes etc. [*Bringi and Chandrasekar*, 2001; *Villarini and Krajewski*, 2010]. To improve the radar-based rainfall estimation, the application of dual-polarization or polarimetric radars could contribute significantly in quality control and correction of radar data [*Villarini and Krajewski*, 2010; *Harrison et al.*, 2015]. However, the model generalizations for all rainfall events in both cold and warm seasons based on the proposed linear models between $\overline{\mathrm{RH}}$ (extracted from the lowest 7 WRF layers) and $\overline{P_{G-R}}$ have effectively indicated that they are highly correlated. Nevertheless, detailed radar data information along with layer selection should be implemented in further analysis. Besides the relative humidity, other meteorological variables (such as wind, which have been investigated on wind-induced error [*Collier*, 1999; *Nešpor and Sevruk*, 1999; *Duchon and Essenberg*, 2001; *Mittermaier et al.*, 2004; *Lack and Fox*, 2007; *Fortin et al.*, 2008; *Lauri et al.*, 2012; *Dai et al.*, 2013, 2015; *Dai and Han*, 2014]) may also play important roles in resulting in radar-gauge rainfall discrepancies. [*Dai and Han*, 2014] proposed a scheme in tackling wind effects on radar-gauge comparison and found it could be helpful in radar rainfall adjustment to some extent. However, the results also showed that radar-gauge rainfall agreement in some cases deteriorated due to the complicated atmospheric conditions and it was not easily to be reproduced as it was region-dependent. Moreover, air pressure which is considered as a key element in evaporation estimation somehow exerting influence on rainfall variation [*Thornthwaite and Holzman*, 1939; *Makkink*, 1957; *Morton*, 1968; *Singh and Xu*, 1997], will also be established in further exploration.

In addition, besides the three-dimensional relative humidity field achieved by downscaling the ECMWF reanalysis data through the WRF model, there are other similar reanalysis data from the National Centers for Environmental Prediction (NCEP), National Aeronautics and Space Administration (NASA), Japanese Meteorological Agency (JMA), etc. [*Dee et al.*, 2014], as well as atmospheric models in obtaining high spatial-temporal resolution products such as Global Forecast System (GFS), General Circulation Model

(GCM), which can be utilized to enhance the above analysis. On top of that, it is still uncertain whether to trust the simulated meteorological products due to the lack of observation data, therefore, the atmospheric sounding files along with ensemble model simulations should be accounted in future work.

5 Conclusions

This study explores the radar rainfall discrepancies induced by relative humidity effects. Six typical rainfall events in the cold and warm seasons are respectively investigated to identify how the rainfall discrepancies between rain gauge and radar vary with changes of relative humidity. The results in both seasons show that the overestimation of rainfall from radar to gauge can be detected when relative humidity is low; the rainfall measured from gauge can be notably increased when relative humidity is at high levels. The linear regression models in both seasons reveal desirable fitting correlations between the mean relative humidity and the average rainfall deficits especially for the rainfall events in the cold season which is incorporated with relatively higher r. The poor fitting correlation in the warm season may be due to the shortage of precipitation and relative humidity data in comprehensively modelling their relationship. Thus, it would be helpful to fill the gap if more data is considered. Nevertheless, the generalization results integrated with the proposed models indicate that radar-gauge rainfall agreement has been improved significantly because of notable decrease of RMSE for rainfall events in cold (from 4.002 mm/h to 1.057 mm/h) and warm (from 4.615mm/h to 1.048 mm/h) seasons.

However, it should be noted the proposed scheme in the current phase is simply a proof of concept in the early-stage of exploring the effects of meteorological variables of relative humidity on radar-gauge rainfall discrepancies in three-dimensional coordinates. More rainfall events along with uncertainties in atmospheric model simulations should be considered in future work not only in improving the quantification of radar-gauge rainfall discrepancies driven by synoptic regimes, but also in implementing the radar rainfall corrections based on this premise. The proposed scheme could be very useful in many meteorological and hydrological applications as it is trialed and improved by the hydro-meteorological community.

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Table 1. The information of rainfall events.

Event ID	**Start Time(YY-MM-DD:HH)**	**End Time**	**Duration(h)**	**Accumulated Rainfall(mm)**
1	2008-06-26:05	2008-06-26:22	18	57.4
2	2008-12-19:12	2008-12-20:00	13	46.4
3	2008-04-29:12	2008-04-30:07	20	45.4
4	2008-02-25:14	2008-02-26:07	18	38.7
5	2008-07-01:16	2008-07-02:02	11	21.4
6	2008-06-01:06	2008-06-01:16	11	19.7

Table 2. Comparisons on Rainfall Events in Cold and Warm Seasons by RMSE (mm/h).

	Cold				Warm			
RMSE*	Event 2	Event 3	Event 4	Overall	Event 1	Event 5	Event 6	Overall
Uncorrected	4.740	3.253	3.139	4.002	4.984	4.230	2.868	4.615
Corrected	0.842	1.344	1.124	1.057	0.678	1.760	0.334	1.048

*RMSE: mm/h

Figure 1. The location of radars (red rectangles) and rain gauges (black dots) distributed in the study area of England, UK.

Figure 2. The $P_{G\text{-}R}$ varies with the increase of $\overline{RH}$ values along with $\overline{RH}$ and $(\overline{P_{G-R}})$ relationship fitted by a two-parameter linear equation in cold (a), (b), (c), (d) and warm (e), (f), (g), (h) seasons respectively.